Photonics

R. Baets – E. Bente

Semiconductor detectors - Part A

Phototubes, Photoconductors

Types of detectors

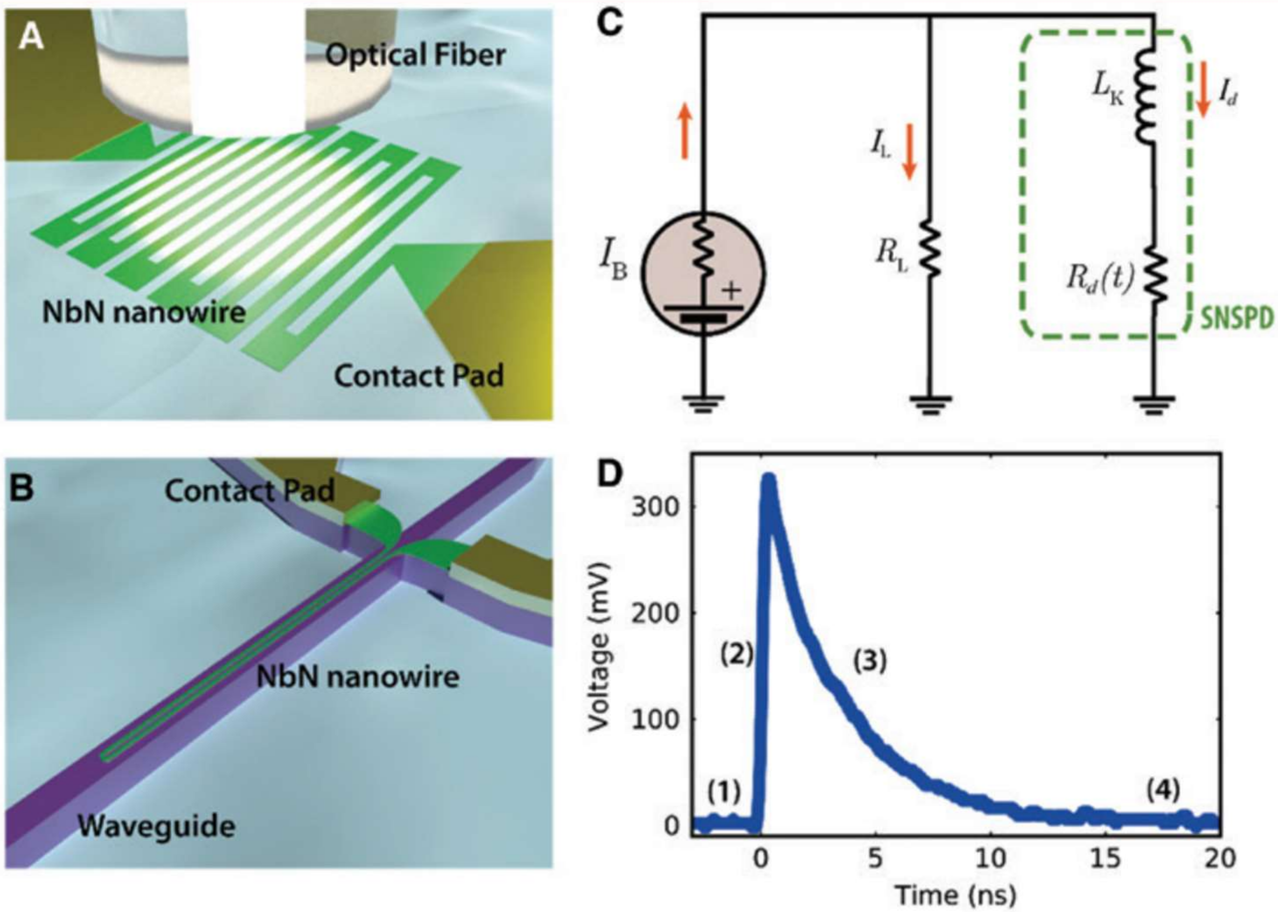
- Bolometers: thermal detectors

  light onto absorbing object ➔
  heating due to optical input power ➔
  measure temperature increase (e.g. temperature sensitive resistance)

- Photo-electric detectors

light ➔ mobile carriers ➔ current

Superconducting nanowire single photon detectors



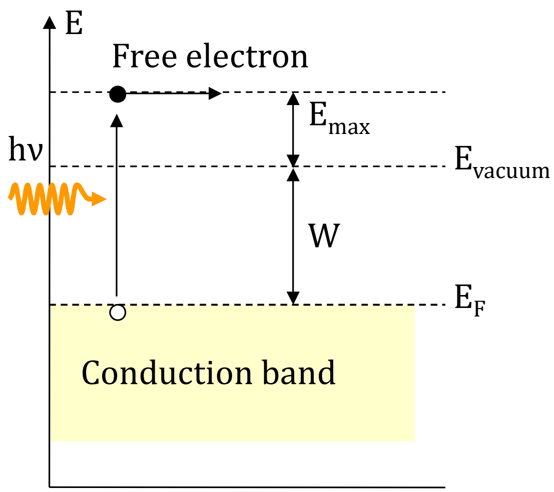
Ferrari, Simone, Schuck, Carsten and Pernice, Wolfram. "Waveguide-integrated superconducting nanowire single-photon detectors" *Nanophotonics*, vol. 7, no. 11, 2018, pp. 1725-1758. https://doi.org/10.1515/nanoph-2018-0059

The photo-electric effect

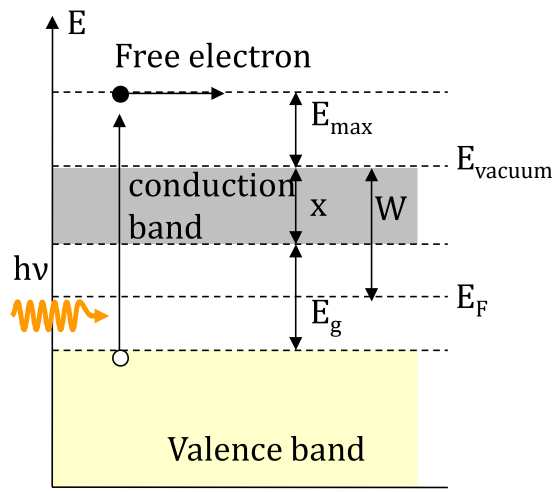
- External: electrons are kicked out of the material
  ➔ photo-electrical emission

- Internal (semiconductors): valence electrons become conduction electrons ➔ photoconductivity

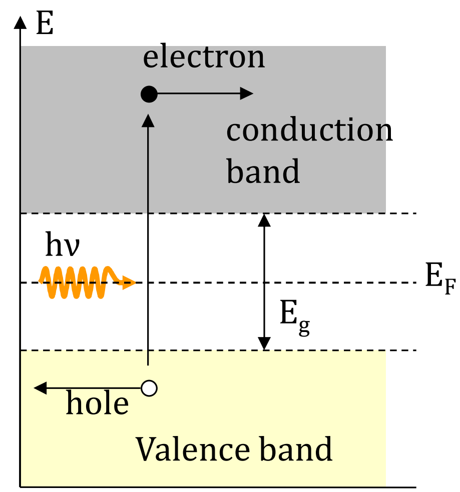
metals



semiconductor

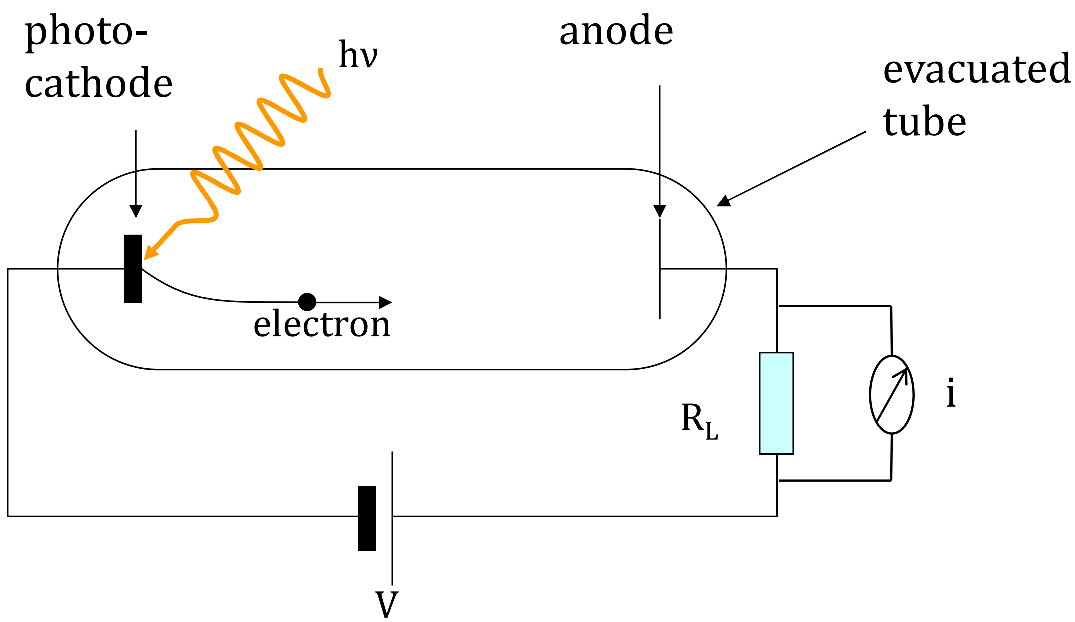


Internal (semiconductor)



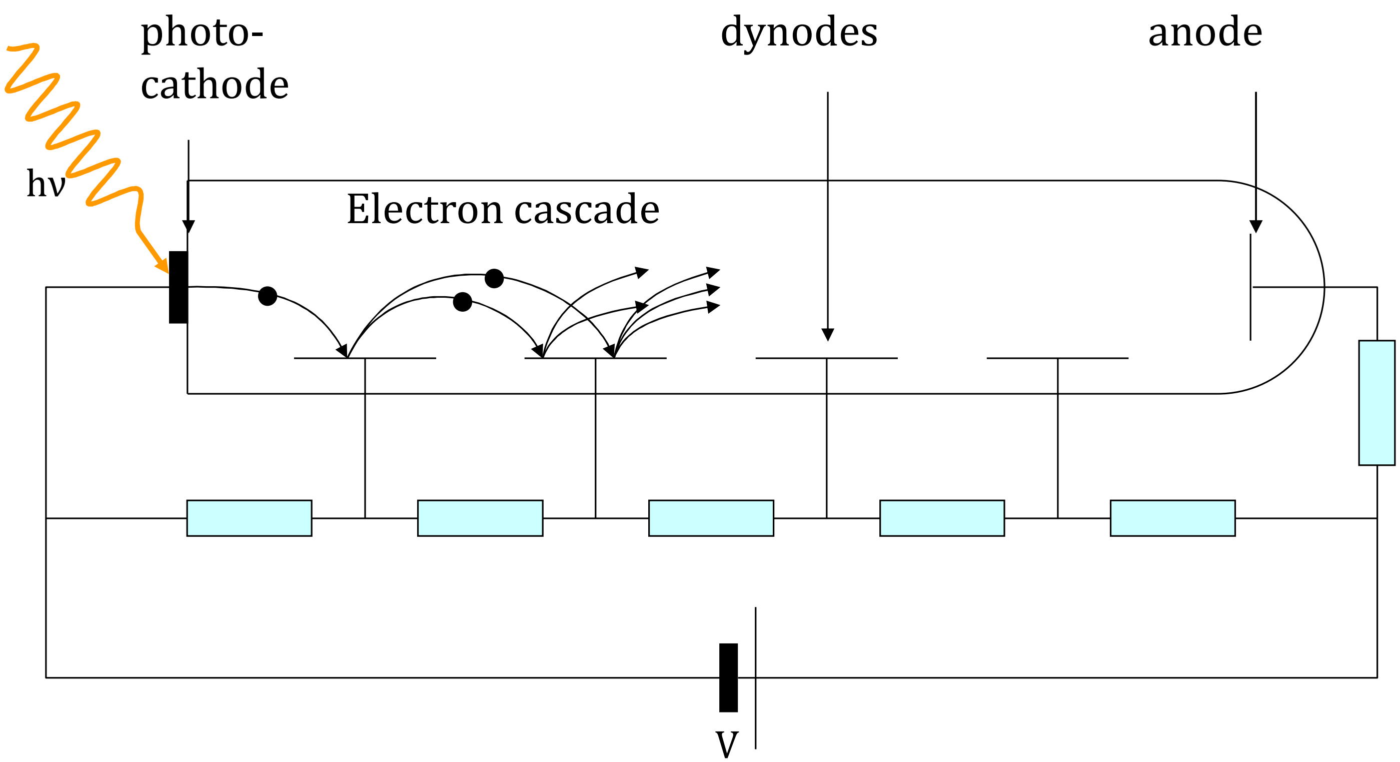
Phototubes

- Free electrons are accelerated to the anode by an electrical field
- Each photon creates max 1 electron
  ➔ Current is proportional to photon flux



Photomultiplier

- Electrons are accelerated and create new free electrons on dynodes: cascade effect
- Can detect single photons



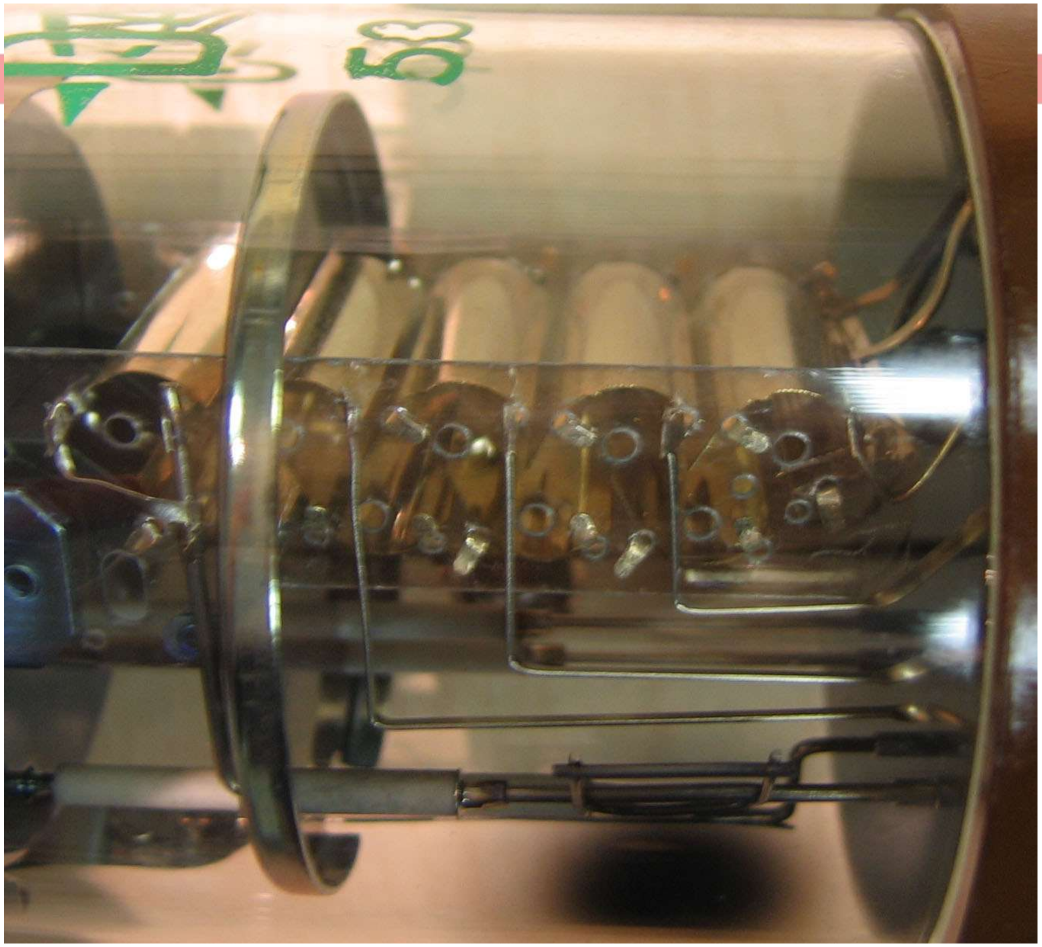
Photomultiplier

Voltage divider
and high voltage
Capacitors to
be connected here

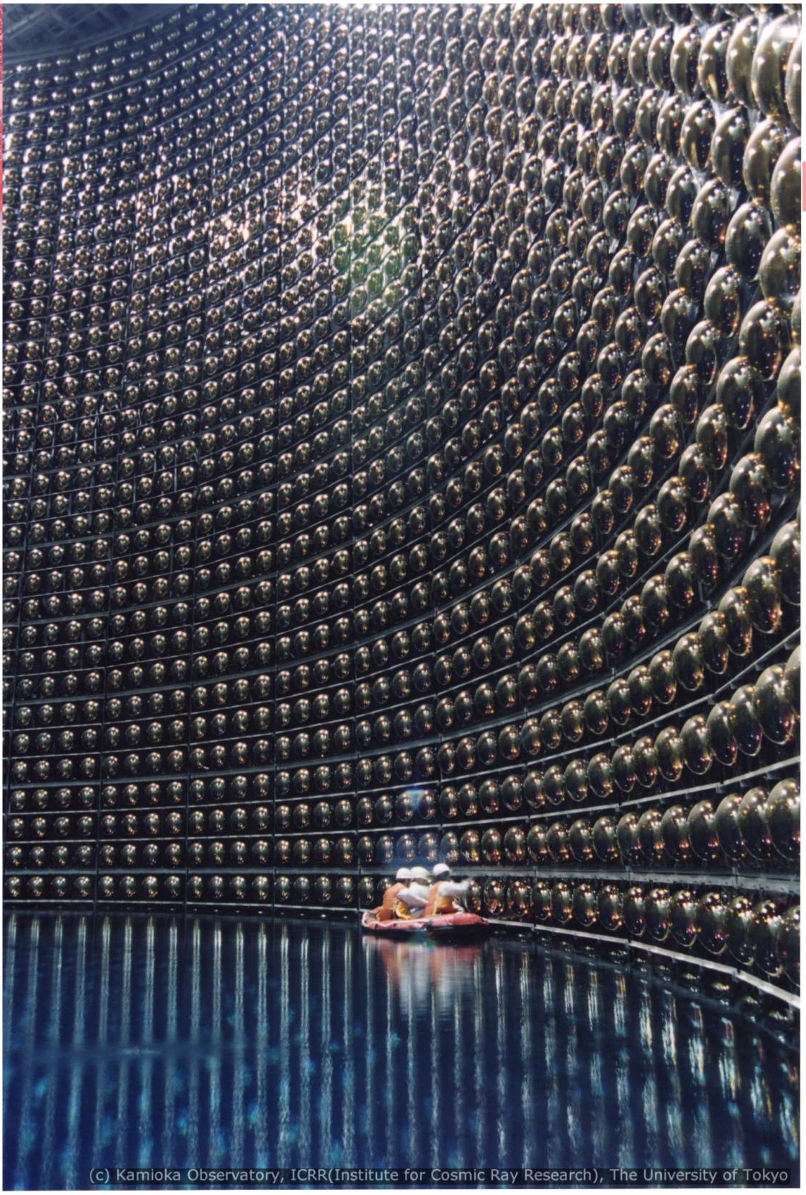
Advantage: ideal current source – large detection area

Photomultiplier tube - Stock Image - C020/7895 - Science Photo Library

Dynodes



Application in neutrino detector



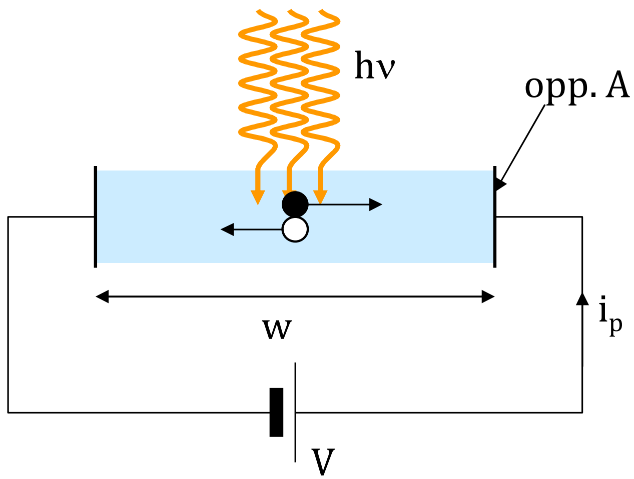
Kamioka Observatory,
University of Tokyo, Japan

11000 PM tubes

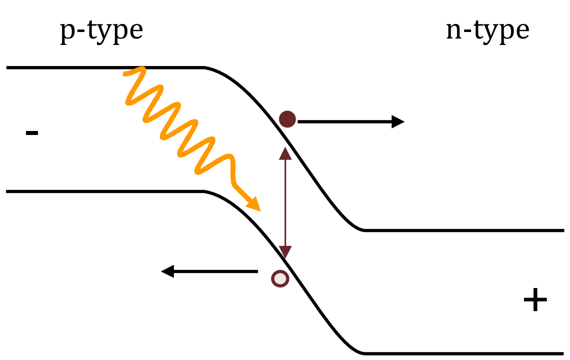
http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html

Semiconductor detectors

- **Photoconductor**
- Light flux is measured through photoconductivity
  - measure resistivity
  - uniform material
    → no doping
    → carrier recombination



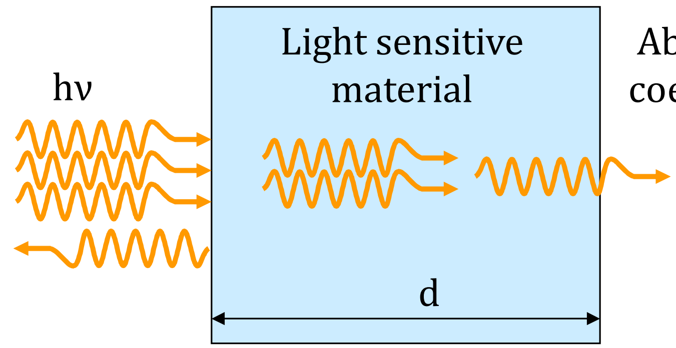
- **Photodiode**
- Light flux is measured through generated photocurrent
  - measure current
  - p-n diode
  → carrier separation



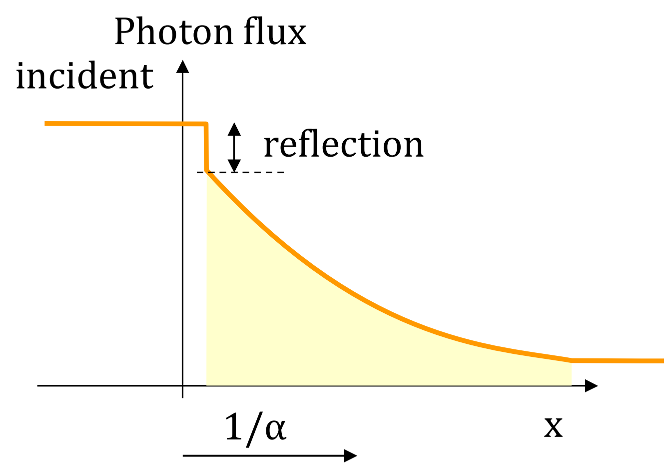
Quantum efficiency

- Quantum efficiency: probability that an incident photon contributes an electron to the photocurrent

- Reduction of the efficiency by
  - Reflection at the surface
  - Exponential decrease of intensity
  - Charge recombination



- Quantum efficiency $\eta = (1 - R)[1 - e^{-\alpha\ \ }]\zeta$
  - R = reflection
  - d = thickness depletion layer
  - ζ = fraction of e^-h^+ pairs that contributes to current
  - α = absorption coefficient

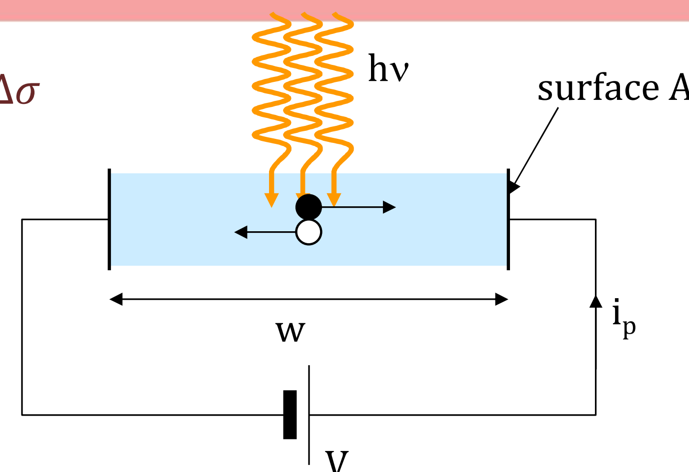


Photoconductor

- Light flux is measured through change in photoconductivity $\Delta\sigma$

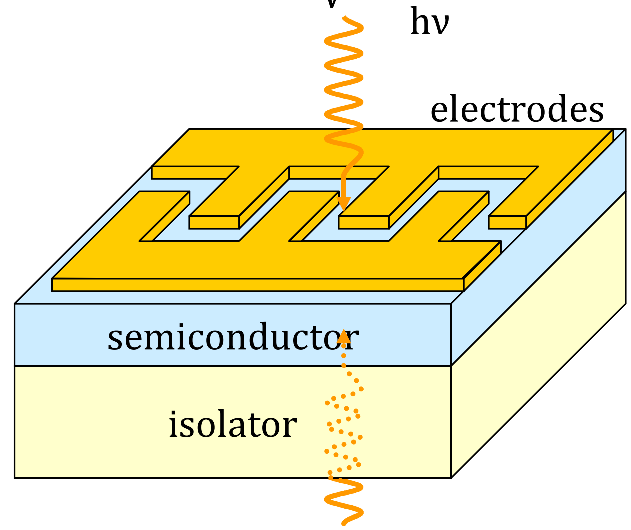
$$\Delta\sigma = e\Delta n(\mu_e + \mu_h)$$

$\Delta n \sim \Phi$	Φ Incoming photon flux
	Δn change in carrier density
$\mu_e \quad \mu_h$	electron and hole mobilities



- Implementation: semiconductor on insulator

- Contacts:
  - large spacing: more light sensitive area
  - close together: faster transit time of carriers
  - → compromise: inter-digitated contact

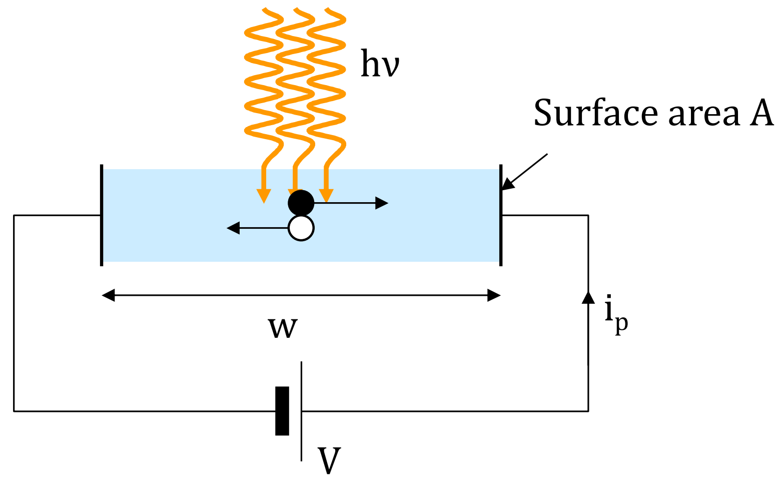


Photoconductor

- Rate of generation of e^-h^+ pairs:

$$G_L = \frac{\eta\Phi}{wA} = \frac{\eta}{wA} \cdot \frac{P_0}{h\nu}$$

  - η = internal quantum efficiency
  - Φ = photon flux



- Recombination rate of e^-h^+ pairs $U = \frac{\Delta n}{\tau}$

  - Δn = photo-electron concentration
  - τ = lifetime of photo-electrons and holes (excess carriers)

- Stationary regime: $G_L = U$ ⇒ $\Delta n = \frac{\eta\tau\Phi}{wA}$

Electron and hole mobility

Δn = photo-electron concentration

τ = lifetime of photo-electron

- Increase of conductivity $\Delta\sigma$ proportional to photon flux Φ

$$\Delta\sigma = e\Delta n(\mu_e + \mu_h)$$

The material specific parameters μ_e and μ_h are the electron and hole mobility.

The mobility parameters relate the drift velocity of the charge carriers and the electric field strength:

$$v_e = \mu_e E \qquad v_h = \mu_h E \qquad \text{Typically:} \qquad \mu_e \gg \mu_h$$

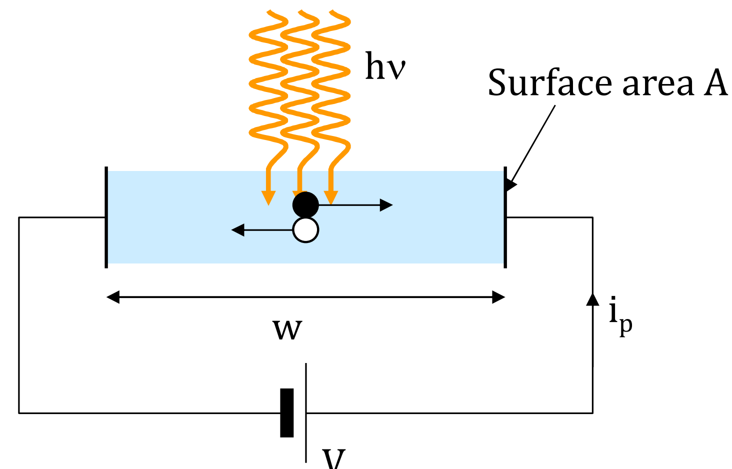
- Increase of conductivity

$$\Delta\sigma = e\Delta n(\mu_e + \mu_h) = \frac{e\eta\tau\Phi(\mu_e + \mu_h)}{wA}$$

Photoconductor

- Uniform electric field in the semiconductor

$$E = V / w$$



- Current density $J_{ph} = \Delta\sigma \cdot E$
- Velocity of the carriers $v_e = \mu_e E \quad v_h = \mu_h E$
- Photocurrent density: $$J_{ph} = \frac{e\eta\tau(v_e + v_h)}{wA}\Phi$$

  Photocurrent: $$i_{ph} = \frac{e\eta\tau(v_e + v_h)}{w}\Phi$$

- transfer time τ_e: $v_h \ll v_e \qquad \tau_e = \frac{w}{v_e}$

$$i_{ph} = e\eta\frac{\tau}{\tau_e}\Phi$$

carrier lifetime / carrier transfer time

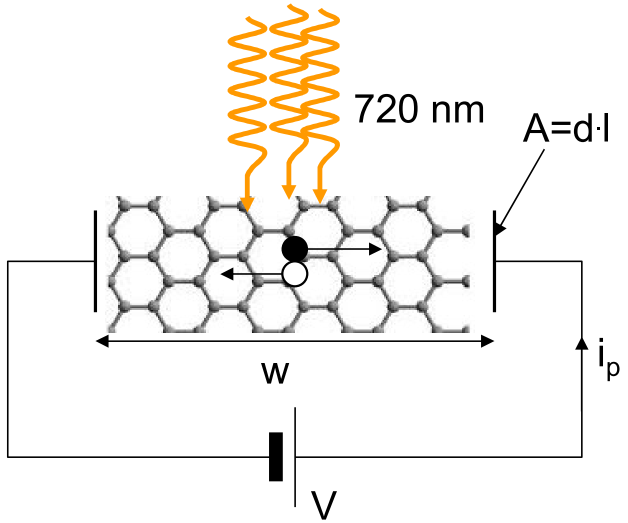
amplification

- Definition of responsivity: $$\Re\left[\frac{A}{W}\right] = \frac{photo\ current}{optical\ power}$$

Exercise: Graphene vs GaAs photoconductor

- we have a photoconductor made from Graphene or GaAs with w=100µm and l=10µm and thickness d
- treat graphene as refractive index 1
- all carriers contribute to photoconductivity

	Graphene	GaAs
μ_e/μ_h[cm²/Vs]	12000/12000	1000/150
d [nm]	0.5 nm	80 nm
α [/cm]	400000	14000
n	1 (for simplicity)	3.6
τ [ps]	4	60



- What is the efficiency in each case?
- We illuminate homogeneously with an irradiance of E^e=1000W/m² at 720nm. What is the current for V=2V?
- What is the efficiency of the combination: graphene on top of 80 nm GaAs?

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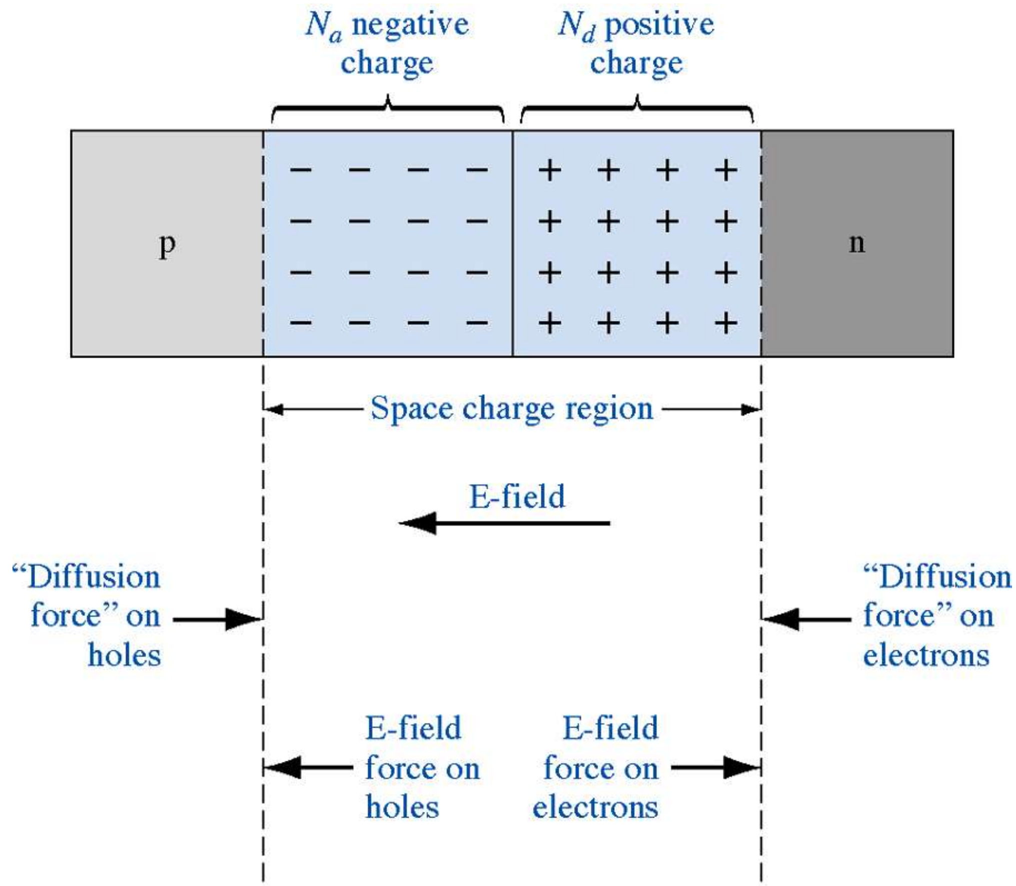
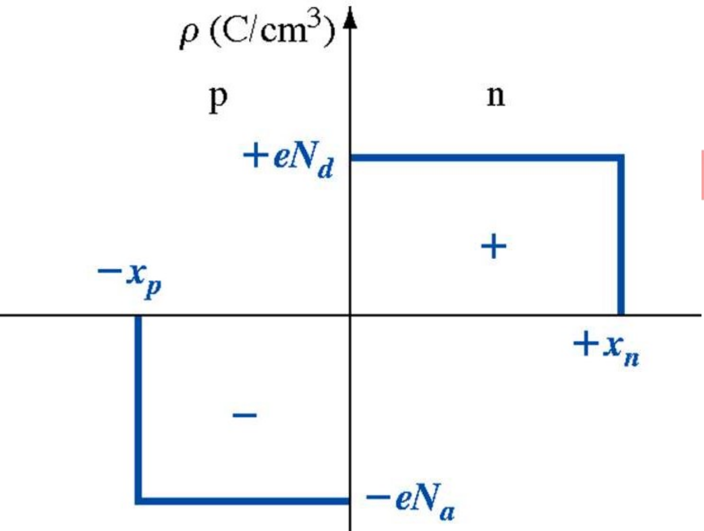
Semiconductor detectors – Part B

Photodiodes

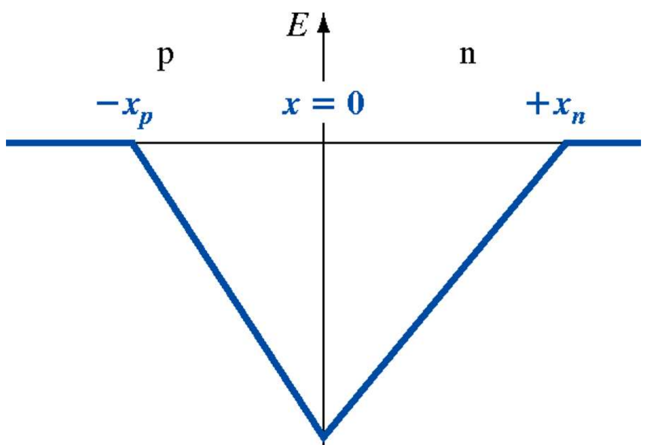
pn-junction recap



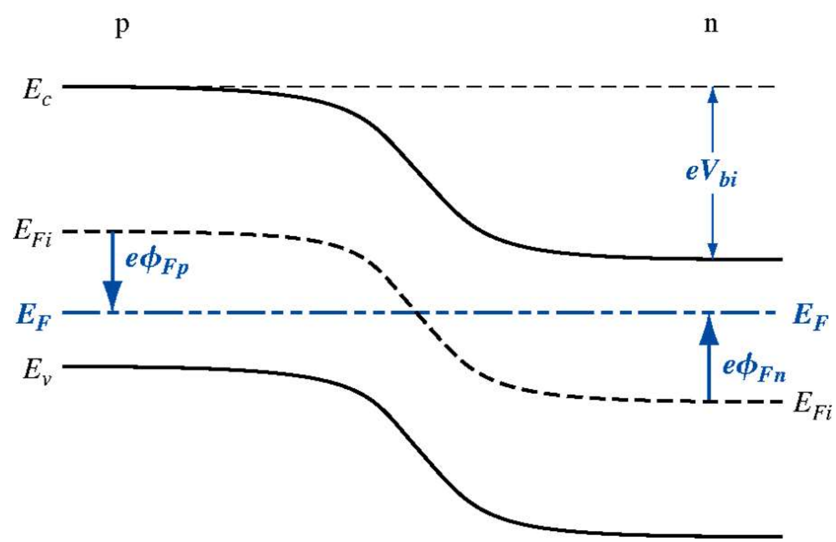
Pn-junction: Built-in potential



Charge distribution



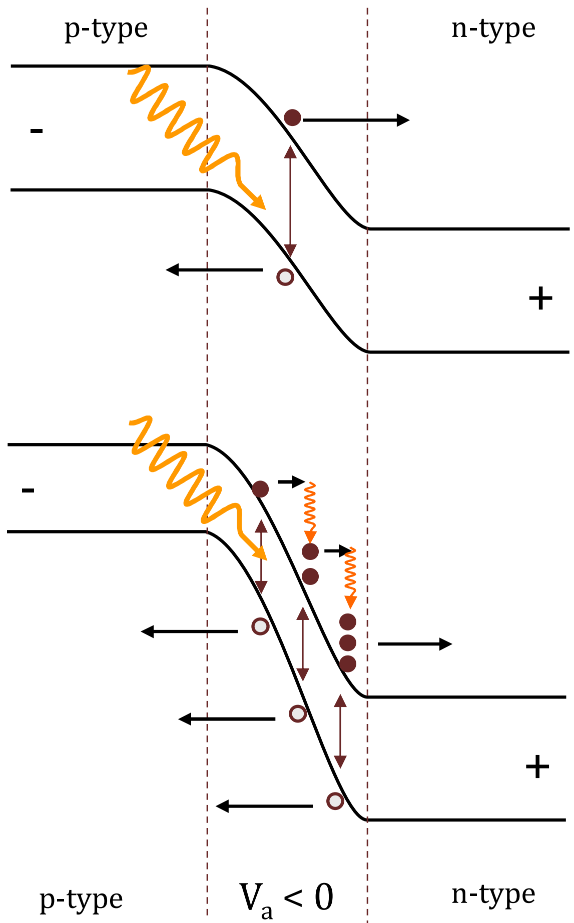
Electric field strength



Electric band diagram

Photodiode

- Photon hits semiconductor
- Absorption leads to e-h pair
- Internal electric field from p-n junction separates electrons and holes and leads to an external current
- At strong internal fields
  - Electrons and holes collide with crystal lattice and give rise to multiple electrons and holes (impact ionization)
  - This leads to internal amplification
  - ➔ Avalanche photodiodes

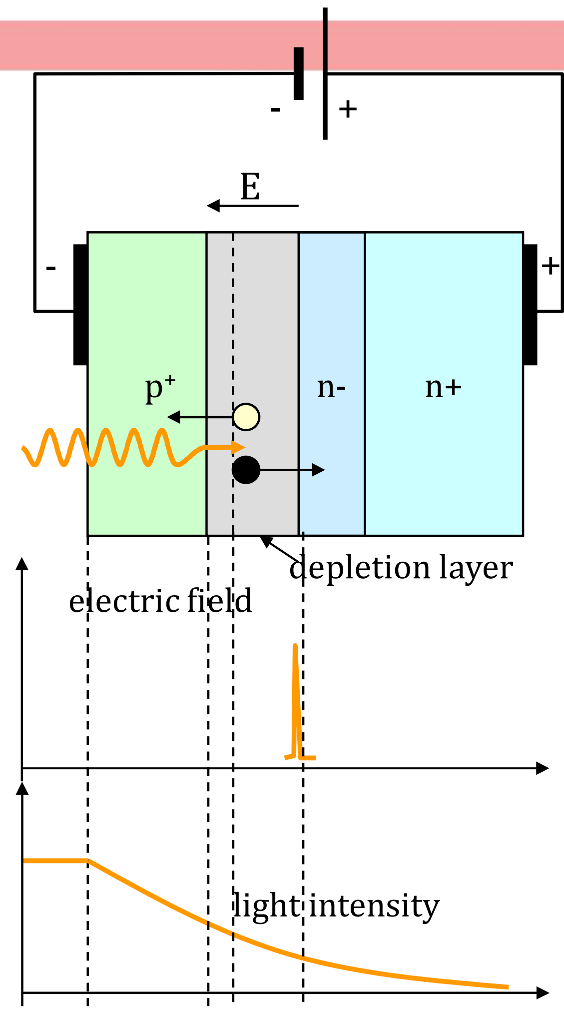


Photodiode structure

- Photodiode= LED
  - LED: forward biased
  - PD: reverse biased

- Created electrons and holes recombine, unless they are created in the depletion region
  → electrons to n-side
  → holes to p-side

- Absorption of incident light
  Fast decrease intensity
  Creation of eh pairs



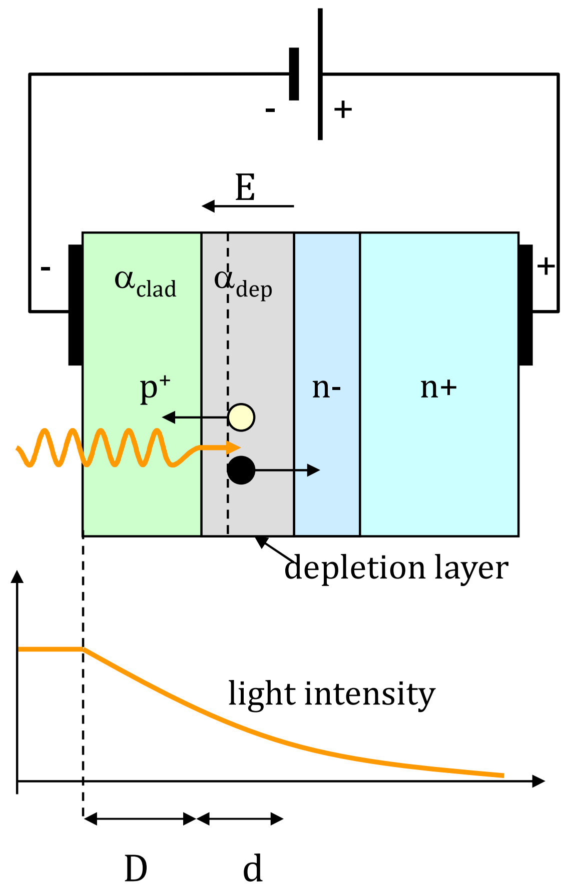
Efficiency

- Reduction of efficiency by
  - Reflection at surface
  - Exponential decrease of intensity: only absorption inside depletion region useful
  - Charge recombination

- Quantum efficiency

$$\eta = (1 - R)\left[1 - e^{-\alpha_{dep} d}\right] e^{-\alpha_{clad} D} \zeta$$

  - R = reflection
  - d = thickness depletion layer
  - D = depth depletion layer
  - ζ = fraction of eh pairs that contribute to current
  - α = absorption coefficient



Diode Responsivity

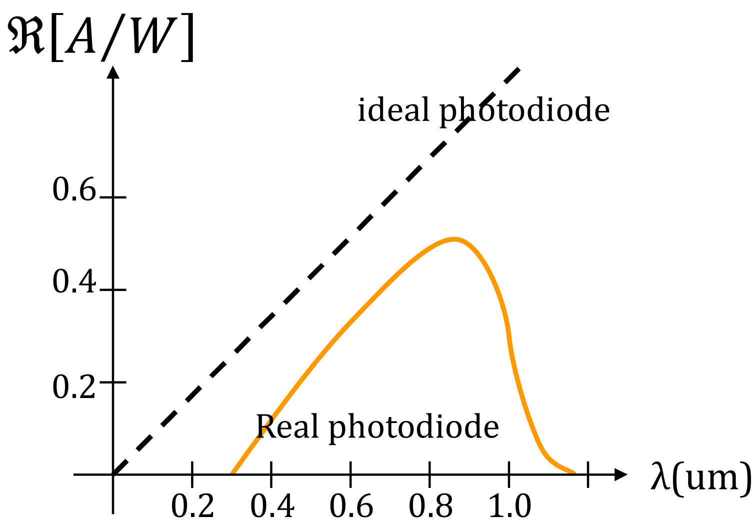
- Ideal photodiode: every photon creates an e^-h^+ pair
  ➔ responsivity

$$\Re\left[\frac{A}{W}\right] = \frac{photo\ current}{optical\ power} = \frac{e}{h\nu} = \frac{e\lambda}{hc}$$

- Non-ideal photodiode

$$\Re = \frac{\eta e}{h\nu} = \frac{\eta\lambda\ [\mu m]}{1.24\ V\ \mu m}$$

  - efficiency < 100% ➔ not all photons are absorbed



- Detector with amplification (avalanche diode, photoconductor)

$$\Re > \frac{e}{h\nu}$$

I-V characteristic of a photodiode(1)

- Diode without incident light
  - Exponentially increasing current when V > 0
  - Almost no current when V < 0 (dark current)

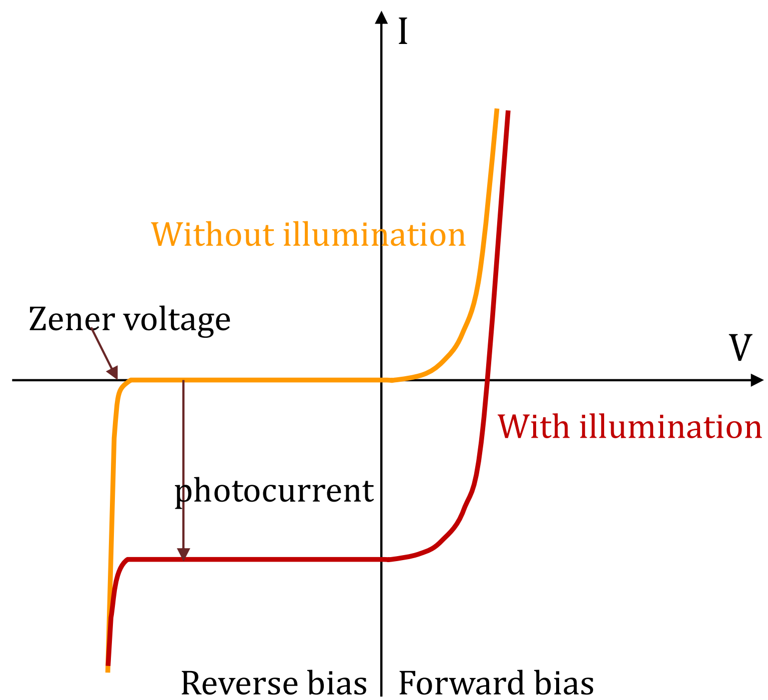
- Under illumination
  - Extra current proportional with incident light intensity
  - Responsivity $\Re$

$$I_{rev} = \eta e \Phi = \frac{\eta e P_{opt}}{h\nu} = \Re P_{opt}$$

$$\Re = \frac{\eta e}{h\nu} = \frac{\eta\lambda\ [\mu m]}{1.24\ V\ \mu m}$$

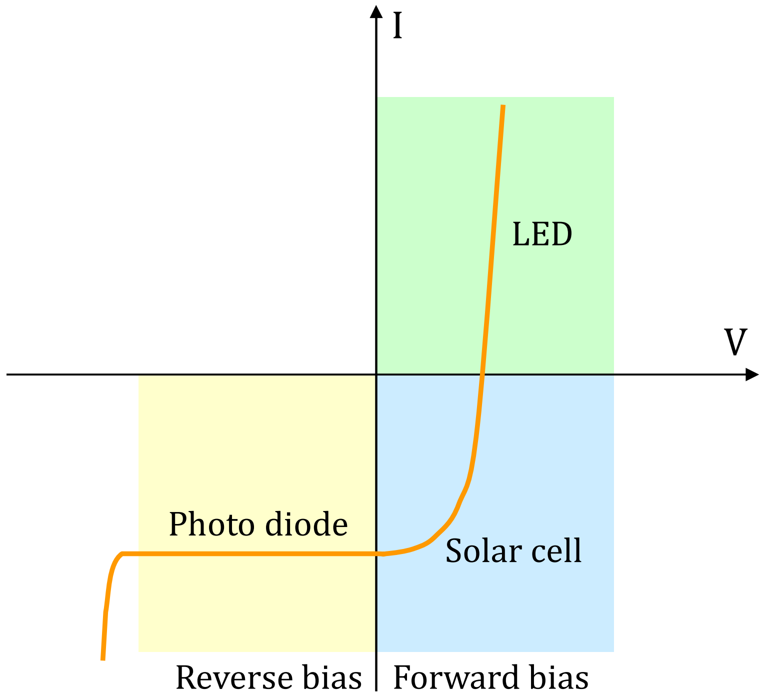
+ optically generated charges

$$J = J_S\left[exp\left(\frac{eV_a}{k_B T}\right) - 1\right] \quad J_S = e\left(\frac{D_n n_{p0}}{L_n} + \frac{D_p p_{n0}}{L_p}\right)$$



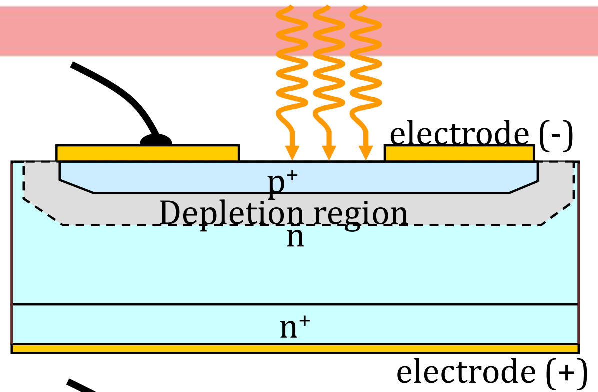
I-V characteristic of a photodiode (2)

- 1^{st} quadrant:
  - Electrical power in ($I{\cdot}V>0$)
  - Light power out
  - ➔ LED-operation
- 3^{rd} quadrant:
  - Electrical power in ($I{\cdot}V>0$)
  - Light power in
  - ➔ Photodiode operation
- 4^{th} quadrant
  - Electrical power out ($I{\cdot}V<0$)
  - Light power in
  - ➔ Solar cell

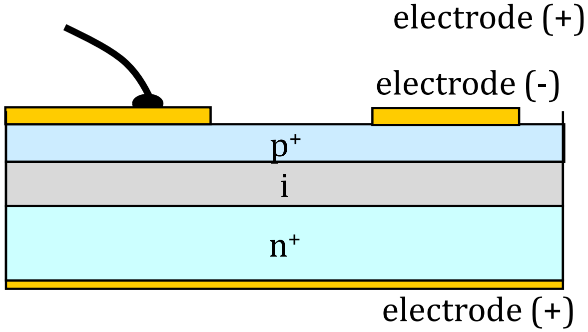


Photodiode designs

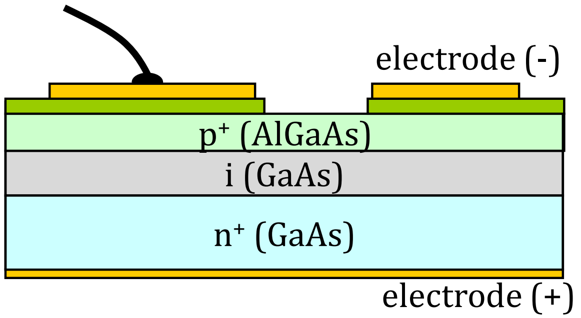
- p-n photodiode:
  absorption in the depletion region (p^+n junction



- p-i-n photodiode
  thicker depletion layer
  → improved absorption



- hetero junction photodiode:
  → wide bandgap p-layer
  → low loss in p layer
  → higher responsivity



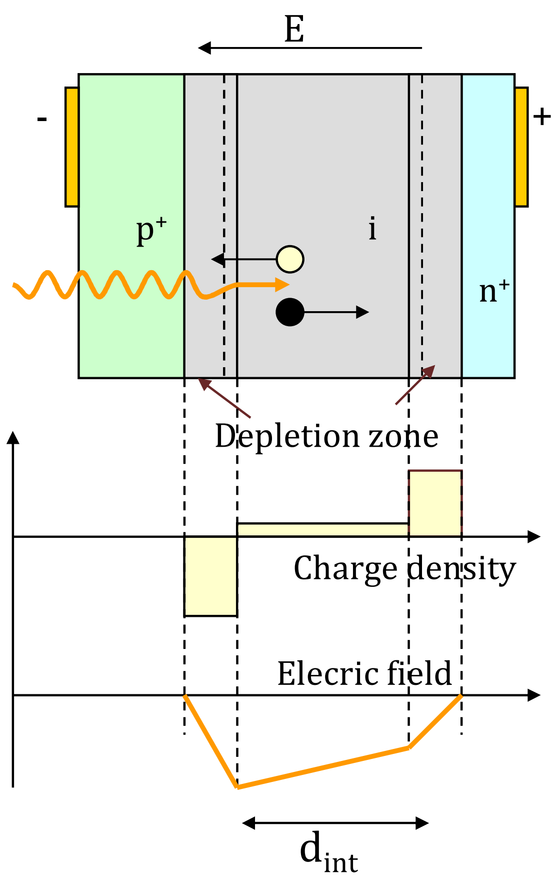
The p-i-n photodiode

- Disadvantage of pn-photodiode: only absorption in thin depletion region
- p-i-n diode: intrinsic layer (i) between p^+ and n^+
- i-layer is much thicker than depletion region
  - Almost no carriers at reverse bias
  - Electrical field at reverse bias

➔ Higher responsivity

$$\eta = (1 - R)\left[1 - e^{-\alpha_{dep} d}\right] e^{-\alpha_{clad} D} \zeta$$

$d \sim d_{int}$



The heterojunction photodiode

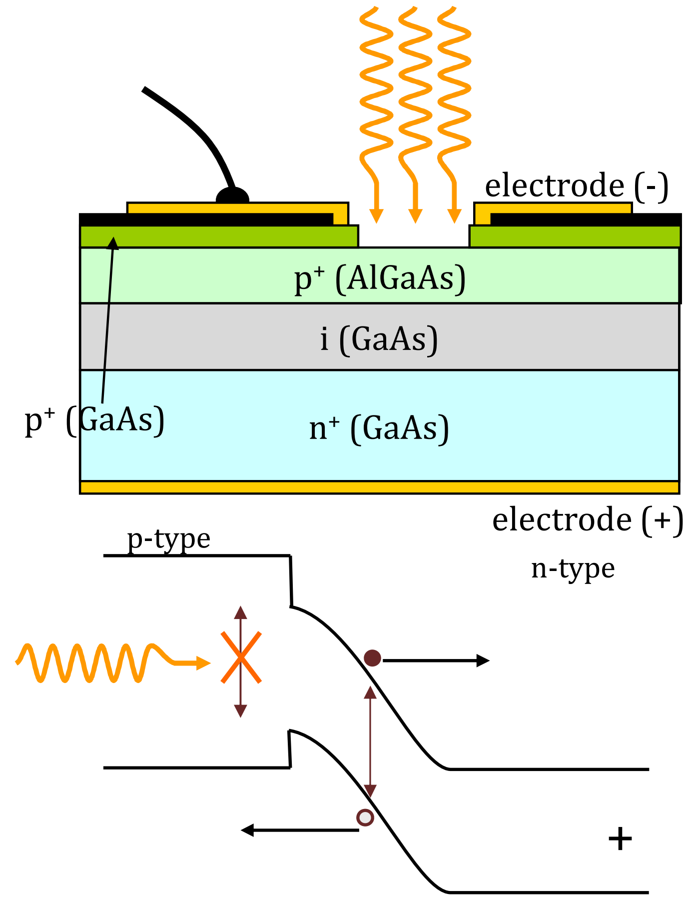
- p-i-n photodiode: absorption close to surface gives rise to surface recombination

  → reduced ζ

- heterojunction-photodiode
  - Surface material has large bandgap
  - ➔ Less absorption in certain wavelength range
  - high quantum efficiency

$$\eta = (1 - R)\left[1 - e^{-\alpha_{dep} d}\right] e^{-\alpha_{clad} D} \zeta$$

$\alpha_{clad} << \alpha_{dep}$



Modulation bandwidth

- Modulation bandwidth: how well do electrical current variations ΔI follow variations in incident power ΔP

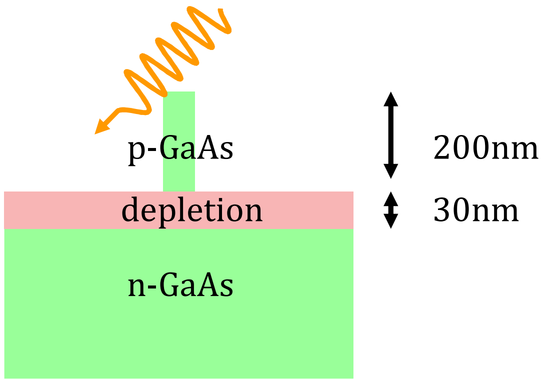
response: $R(f) = \frac{\Delta I}{\Delta P} = \frac{R(0)}{\sqrt{1 + 4\pi^2 f^2 \tau^2}}$ $P(t) = P_0 + \Delta P sin(2\pi f \cdot t)$

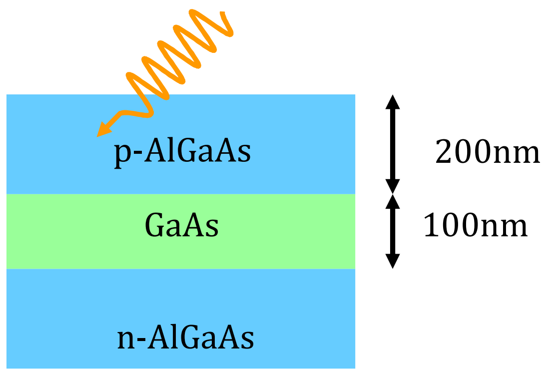
- The modulation bandwidth is limited by
  - the time it takes for the carriers to be collected at the contacts τ (10-100 ps)
  - limited by RC time constant: $f_c = \frac{1}{2\pi RC} = \frac{1}{\tau}$
  - fixed load resistor

→ Reduce C
→ Make diode as small as possible

Exercise: pn vs hetero junction

- Compare the efficiency of a pn and a heterostructure pin diode with the following structure, assume all charges are extracted:



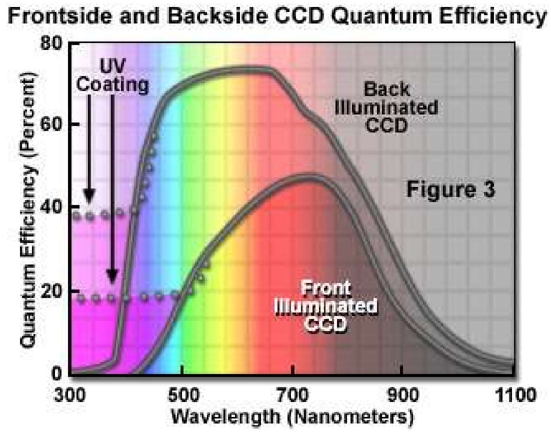


	n	α (780 nm)
GaAs	3.6	12000/cm
AlGaAs	3.4	100/cm

- In each case how much optical power at 780nm is needed to generate 1mA ?

Image sensors

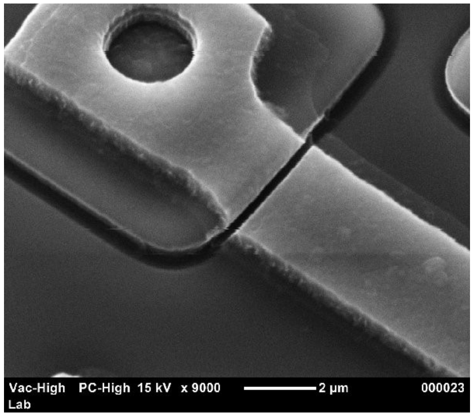
- Matrix of photodetectors (pixels); register photon flux as function of place and time
- Operation
  - photons generate free carriers
  - carriers are being collected / measured
  - processing of measurement results
  - ➔ picture

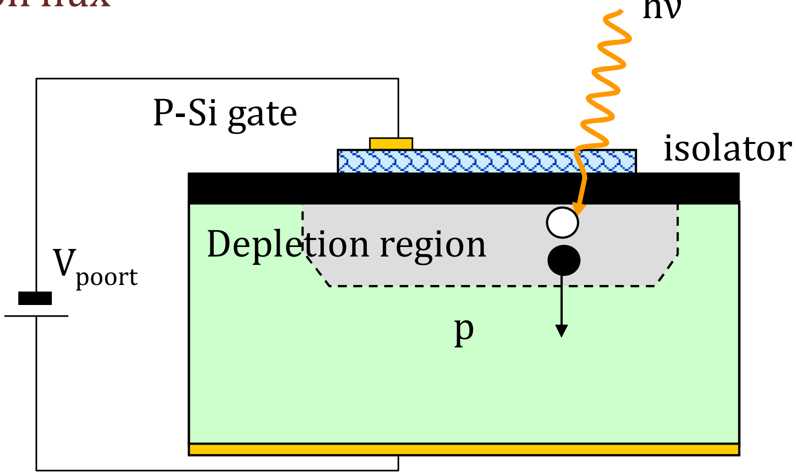


- Two important types
  - CCD (Charge coupled device): charges in a pixel are brought to the side of the chip and are measured there (converted to voltage)
  - CMOS sensor: every pixel has its own circuit to transfer charge to voltage

Charge collection in a MOS capacitor

- MOS = Metal – Oxide - Semiconductor
- MOS-capacitor: p-Silicon with isolator
  - Positive voltage on metal creates depletion region with negative space charge
  - Photon creats e^-h^+ pair in depletion region
  - h^+ migrates to p-region
  - e^- trapped at isolator
- Collected charge proportional to integrated photon flux

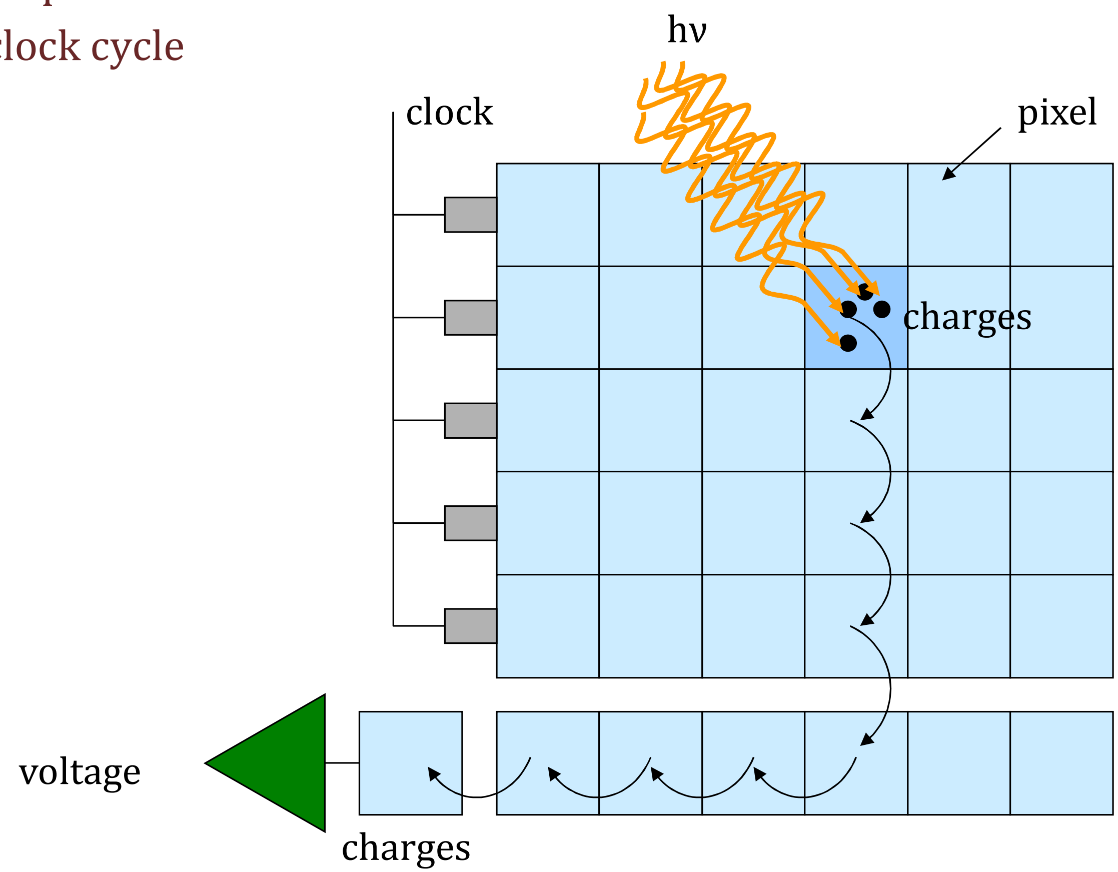




Charge Coupled Device (CCD)

- Charge is created on MOS capacitor
- Transfer charge at every clock cycle to neighbouring pixel
- At the edge
  ➔ voltage conversion

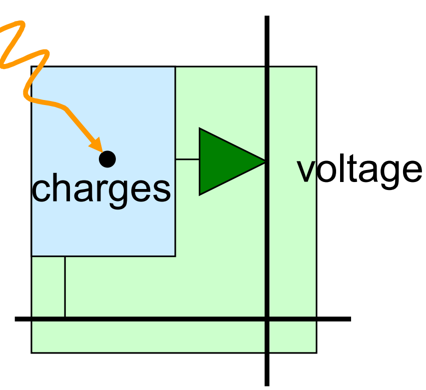
- Advantage
  - High sensitivity
  - Large useful area
- Disadvantage:
  - Relatively expensive
  - Serial read out (slow)

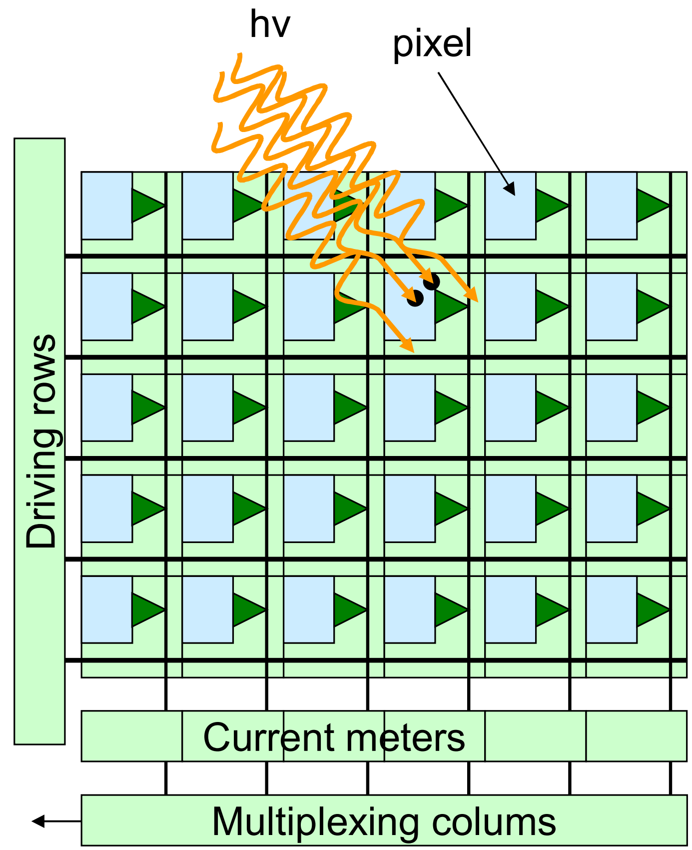


CMOS image sensor

- Every MOS capacitor has its own circuit

- Advantage:
  - Cheap fabrication
  - Random access readout
  - Faster
- Disadvantage:
  - Less useful area
  - More noise





Color cameras

- Film: layers sensitive for red, green, blue
- Digital camera: interleaved pixels with R,G or B filter
- New: 3 CMOS-sensor layers for the 3 colors on top of each other ➔ red penetrates deepest in Silicon